

Brent Wiesenbergl ATK Thiokol Propulsion, (435) 863-6602
Doug Smith, ATK Thiokol Propulsion, (435) 863-8133
Kyle Speas, ATK Thiokol Propulsion, (435) 863-3255
Adam Corliss, ATK Thiokol Propulsion, (435) 863-2971

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MEASURING THE INTERNAL ENVIRONMENT OF SOLID ROCKET MOTORS DURING IGNITION

ABSTRACT

A new instrumentation system has been developed to measure the internal environment of solid rocket test motors during motor ignition. The system leverages conventional, analog gages with custom designed, electronics modules to provide safe, accurate, high speed data acquisition capability. To date, the instrumentation system has been demonstrated in a laboratory environment and on subscale static fire test motors ranging in size from 5-inches to 24-inches in diameter. Ultimately, this system is intended to be installed on a full-scale Reusable Solid Rocket Motor. This paper explains the need for the data, the components and capabilities of the system, and the test results.

BACKGROUND

The ignition transient of solid rocket motors is a highly dynamic event and difficult to accurately simulate with computer models. Performance parameters such as maximum head-end pressure rise rate, joint pressure rise rate, pressure drop down the bore, maximum operating pressure, and propellant mechanical properties during ignition are critical design considerations. Different models are used to describe motor ignition including traditional 1-D and 2-D approaches and emerging computational fluid dynamics (CFD) and 3-D propellant grain models. Most of the current models use laboratory and subscale test motor data to describe the ignition event but accurate, full-scale motor data are critical to conclusive modeling of motor ignition.

Modeling the ignition transient of the Reusable Solid Rocket Motor (RSRM) has proven a particularly difficult task. The relatively high pressure rise rates in the RSRM are higher than predicted and not seen in other similar, large solid rocket motors. Understanding the RSRM ignition mechanisms is desirable.

In order to increase understanding and accurately characterize the RSRM ignition transient, an instrumentation system has been developed to capture the internal motor environment for approximately the first second of motor operation. Many issues must be addressed in order for the instrumentation system to be acceptable for use in the RSRM including safety, reliability, data accuracy, size limitations, motor egress, thermal protection, debris, and material compatibility. Two different approaches have been investigated: a pure fiber optic system (fiber optic gages and fiber optic links) and a hybrid analog/fiber system (analog gages, custom design electronics, and wire and fiber optic links). The latter is described in this paper.

INSTRUMENTATION SYSTEM COMPONENTS AND CAPABILITIES

Maximum flexibility has been designed into the instrumentation system to accommodate a variety of measurements. The system used for motor ignition consists of analog gages (pressure, heat flux, and strain) mounted on the propellant surface, custom electronics boards (front end boards, fiber/wire interface boards) buried in insulation, copper wires, plastic and glass fiber optic cables, and a stand-alone data acquisition computer (See Figure 1). Pressure, heat flux, and strain gages were chosen to provide data for ballistics, CFD, and propellant structural models. The electronics can be used with other types of gages, as well.

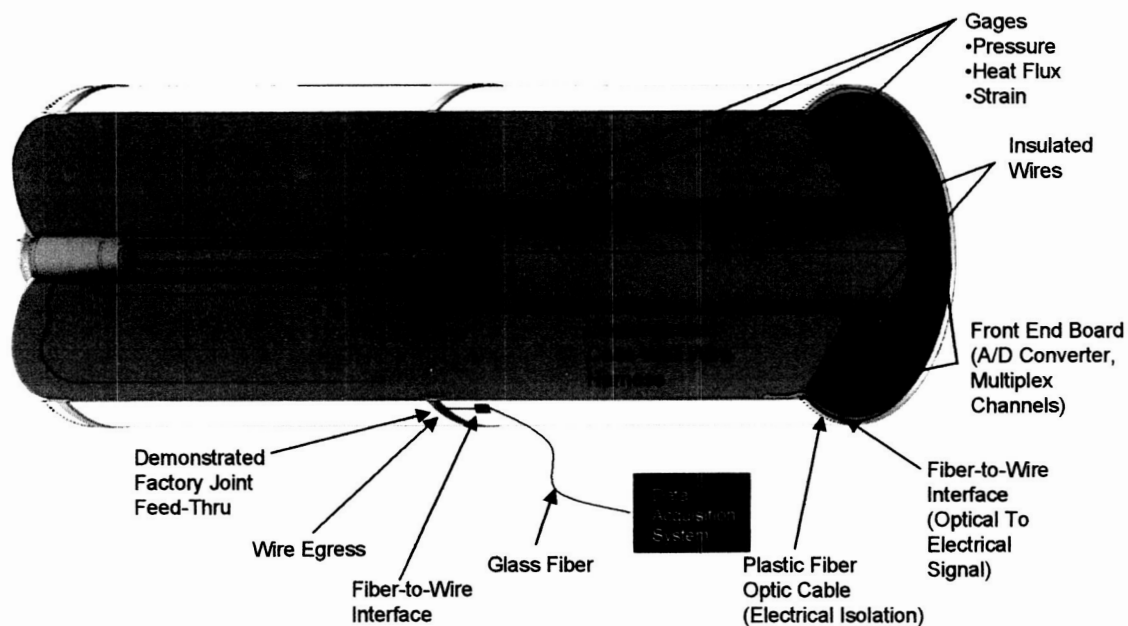


Figure 1. Instrumentation System Components and Sample Layout

Pressure Gage

A compact, off-the-shelf pressure gage with a range of 1000 psi was chosen for use on the propellant surface. Gage dimensions are approximately 0.125 in. wide by 0.30 in. long by 0.05 in. high. A protective, thin layer of thermal protection system (TPS) material is bonded to the gage diaphragm (0.125 in. diameter) then the pressure gage is cast and cured in a propellant module with the TPS covered diaphragm exposed. The pressure gage is shown in Figure 2.

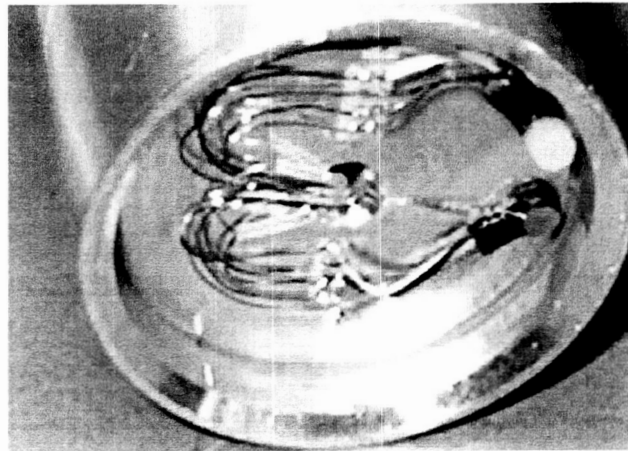


Figure 2. Pressure Transducers With and Without TPS on Diaphragm

Heat Flux Gage

Figure 3 shows the heat flux gage design. This gage is a variation of the standard foil gage. It is designed to survive approximately 0.30 seconds in a solid rocket motor to capture the heat flux during initial propellant grain heating and ignition. The silver slug provides quick thermal response. The black coating was added after initial testing to improve repeatability. In order to minimize undesirable heat effects from the sides and bottom, a ceramic holder was created to accommodate the silver slug.

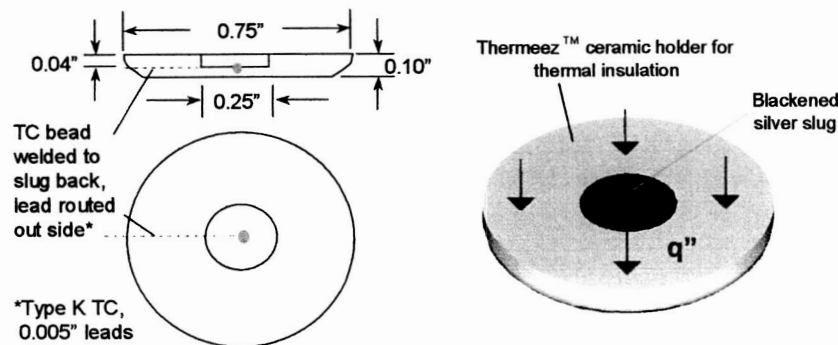


Figure 3. Heat Flux Gage Design

Strain Gage

Because propellant strain during ignition can be greater than 5%, standard foil strain gages are not adequate. A new gage, utilizing a Hall Effect sensor and magnet, was designed to meet this need. Figure 4 shows the gage with TPS installed on a propellant sample. The dimensions of the Hall Effect sensor are approximately 0.13 inches by 0.13 inches by 0.05 inches. The magnet dimensions are 0.5 inches in diameter by 0.1 inches thick and composed of samarium cobalt.

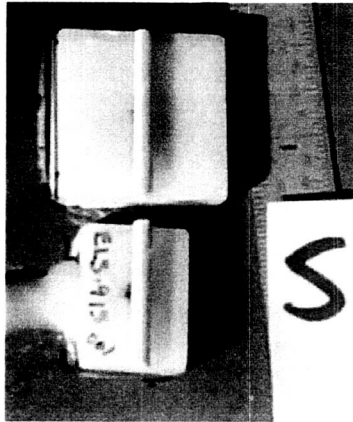


Figure 4. Hall Effect Strain Gage

Front End Board

The front end board (FEB) is the heart of the electronics in the instrumentation system. It provides power to the pressure and strain gages using a 6 volt battery. In its current application, the FEB can operate up to 8 individual channels. Data are collected and transmitted at 2300 samples per second per channel in a controlled manner that can be identified as individual channels by the data acquisition system. Analog gages are connected to the FEB with 0.010 inch diameter copper wire. The FEB converts the analog signals from the gages into digital optical signals and multiplexes the data for transmission over plastic optical fibers inside the motor. The FEB is packaged in an aluminum cover and potted in with a non-electrically conductive compound to provide protection and ease of installation. Figure 5 shows the FEB package that measures about 2 inches by 2 inches by 0.8 inches. A major concern with the FEB was the presence of an energy source so close to the propellant surface. Several layers of safety features have been integrated into the FEB which is mounted in motor case rubber insulation at a safe distance from the propellant. Two safety features limit the total amount of current available on the board in general and also limit current available to individual gages. An additional safety feature is the output of the battery system is limited so that its electrical energy is not sufficient to ignite the propellant even when directly shorted.

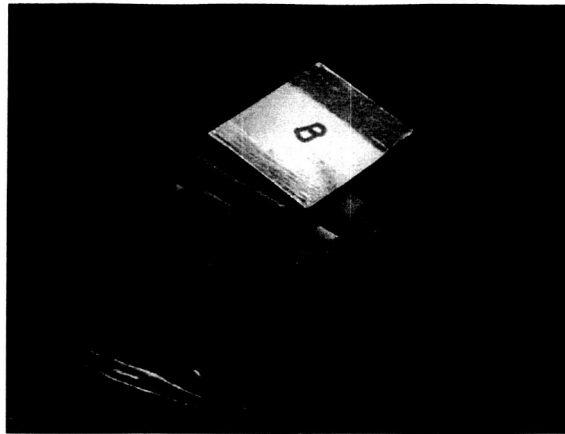


Figure 5. Front End Board

Fiber/Wire Interface Board

The second electronics board in the instrumentation system is the fiber/wire interface board (a.k.a. FWF). Two FWFs are used in the instrumentation system: one internal to the motor and one external. The internal FWF provides a conduit for data from up to 10 front end boards and converts their optical signals to electrical. The data are sent to the external FWF over a copper wire harness and case feed-through system that was developed earlier for insulation erosion measurement gages and has been demonstrated on several full-scale RSRM test motors. The external FWF then converts the electrical signal back to optical and transmits it over glass optical fiber to the receiver board and data acquisition system. Figure 6 shows the FWF package which includes the electronics, aluminum cover, and potting compound. It measures about 3.5 inches by 2.0 inches by 0.8 inches. Power to the internal and external FWFs is supplied by an external source.



Figure 6. Fiber/Wire Interface Board

Other Components

There are several other important components of the instrumentation system: optical fibers, receiver board, and data acquisition system. As was mentioned, plastic optical fiber is used in the motor between the FEB and FWF and its main purpose is to provide

electrical isolation between the propellant grain and sources external to the motor. Plastic fiber was chosen because it is robust and tolerates the installation process well. Glass fiber is used outside the motor because the data can be sent over long fiber lengths without degradation thus allowing greater stand-off distance and protection for the data acquisition system. The receiver board converts the optical signal back to electrical and separates the data into its original channels for storage in the data acquisition system. The data acquisition system uses a standard personal computer with a high speed interface card to handle the high sample rate data stream.

TEST RESULTS

The gages and instrumentation system described above have been demonstrated in a laboratory environment and subjected to solid rocket motor internal temperatures and pressures in multiple subscale tests. One such subscale test configuration is shown in Figure 7. The left pictures shows instrumented segments. The right hand picture shows a motor stack. This test configuration demonstrates partial system functionality and performance with all gages located inside the motor on the propellant surface but all electronics are located external to the motor. Up to six 5-inch CP segments are stacked in a test motor to provide high mass flow and a measurable pressure drop. Figure 8 shows the seventy pound charge (SPC) motor configuration which allows the internal components of the instrumentation system (gages and electronics) with multiple harnesses to be exposed to the internal motor environment. Another test motor configuration that allows the internal components of the instrumentation system to be tested is shown in Figure 9, the 24-inch solid rocket test motor (SRTM). The instrumentation configuration in the 24-inch SRTM is very similar to the SPC configuration and it demonstrates scale-up.

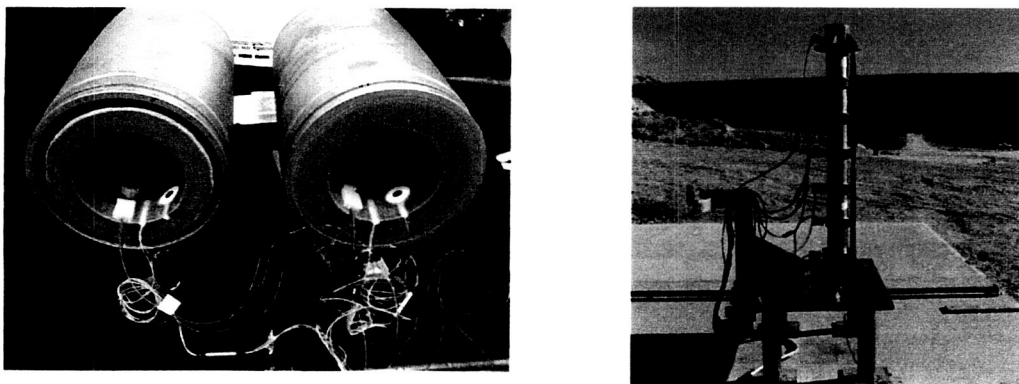


Figure 7. 5-inch CP Segments and Test Configuration

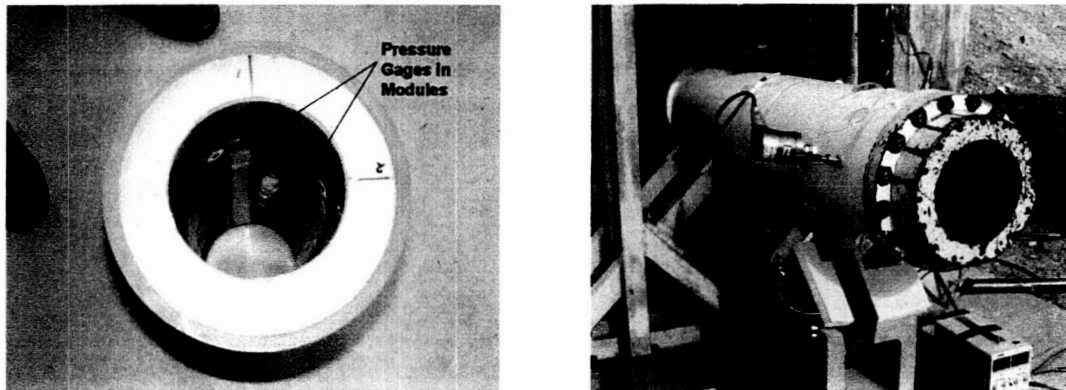


Figure 8. Seventy Pound CP Segment and Test Configuration

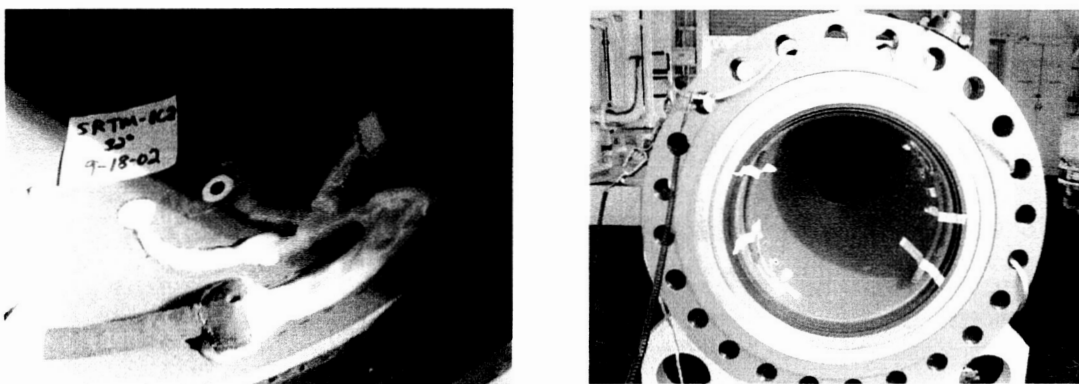


Figure 9. 24-inch Solid Rocket Motor Configuration

Numerous laboratory and hotfire tests have demonstrated the capabilities and reliability of the custom design electronics parts (FEB and FWF) of the instrumentation system. Lab testing of the electronics boards demonstrated the extremes of operating temperature in oven tests. The electronics have functioned at temperatures above 135 deg F and recovered after cooling off from 150 deg F with no loss of accuracy. One hotfire test showed a board was still functioning when the exterior of its aluminum box was close to 500 deg F. Hotfire testing showed that the safety features on the FEB could shut down the entire board because of high current on one channel due to thermal degradation of the wires or gage. An upgraded design added current limiting capability to individual channels thus maximizing the data collection opportunity. The electronics have been thoroughly tested and no further work is necessary.

The chosen pressure gage functions well in laboratory tests but has not demonstrated repeatable results in the hotfire tests. In laboratory testing, the gage has demonstrated the ability to accurately track the rapid pressurization rate of solid rocket motors. In

subscale, hotfire testing, the accuracy of the gage has been less successful due to thermal and other effects. Typically, the gage follows the initial pressurization curve but then an unidentified interaction of effects degrades its accuracy. Figure 10 shows results of initial pressure gage testing in a subscale motor test that exhibited expected performance; thermal degradation of the gages after steady state pressure is reached. The bore gages are noted in the Legend as "Button" gages and were at two locations in the motor. The standard gages are noted as "Taber" gages and are located adjacent to and between the "Button" gages. Figure 11 shows typical data where undesirable effects have impacted the gage performance. The bore gages are noted as P001 (Internal) and P002 (Internal) and do not follow the standard gages very well after the initial pressure rise. Further work is planned to investigate the potential factors affecting gage performance including thermal effects, module processing and handling, gage alignment, and the installation procedure.

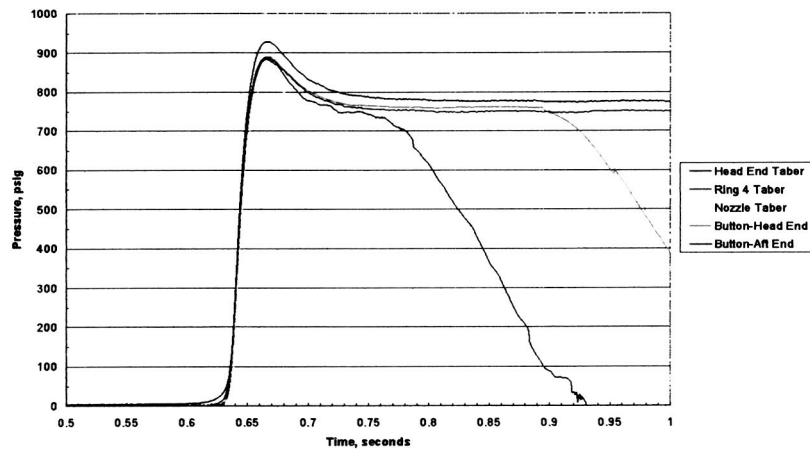


Figure 10. Initial Pressure Transducer Results

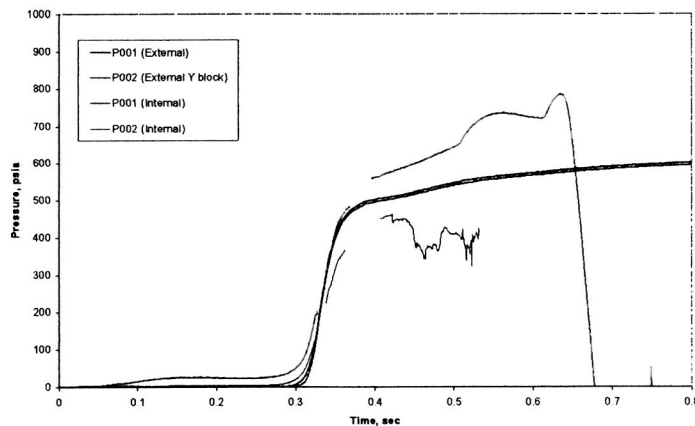


Figure 11. Typical Pressure Transducer Results

The heat flux gage has performed well and provided excellent results in both laboratory and hotfire motor testing. Figure 12 shows test results of the heat flux gage in a laboratory test. Similar results have been demonstrated on subscale motor tests. Because this gage has performed as designed and provided accurate and consistent data on all motor tests, no further design work is required.

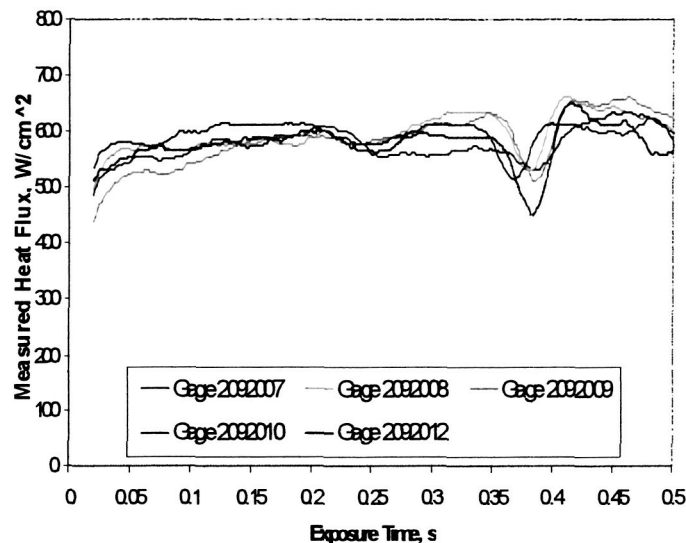


Figure 12. Heat Flux Gage Performance

Future use of the strain gage incorporating the Hall Effect sensor and magnet is in question. Laboratory testing demonstrated the accuracy of the design concept but, when TPS was added to the gage, the accuracy was not sufficient for use in propellant grain structural models. Previous testing with minimal TPS demonstrated acceptable accuracy. Debris concerns associated with nozzle impact from the magnet are also a concern with this design, and testing is underway to address this. Nozzle analysis shows a potential issue but subscale motor tests with up to four magnets have not experienced any problems. Another concern is the method to bond the gage to the propellant surface. Precise orientation of the sensor and magnet is required so a quick drying adhesive is desired but these adhesives typically have undesirable mechanical properties compared to the propellant. Accurate measurement of propellant strain is critical to proper assessment of grain behavior and possibly the most important measurement in this system. Unfortunately, it has also proven to be the most difficult. Work is continuing to qualify an acceptable strain gage by modifying the present design and looking into other acceptable configurations.

CONCLUSIONS

The instrumentation system described in this paper shows the potential to capture the ignition transient in solid rocket motors; a very dynamic and difficult environment to measure and assess. Custom electronics combined with analog gages can provide very

accurate, high sample rate data to help assess the ignition transient through improved ballistics, CFD, and structural models. Work is in-progress according to a comprehensive laboratory and subscale motor testing program to prove the safety and feasibility of the system in preparation for installation on a fullscale RSRM. The electronics components of the instrumentation system can be adapted for other uses where a safe, compact, robust system capable of collecting multiple, diverse channels of high sample rate data is desired.